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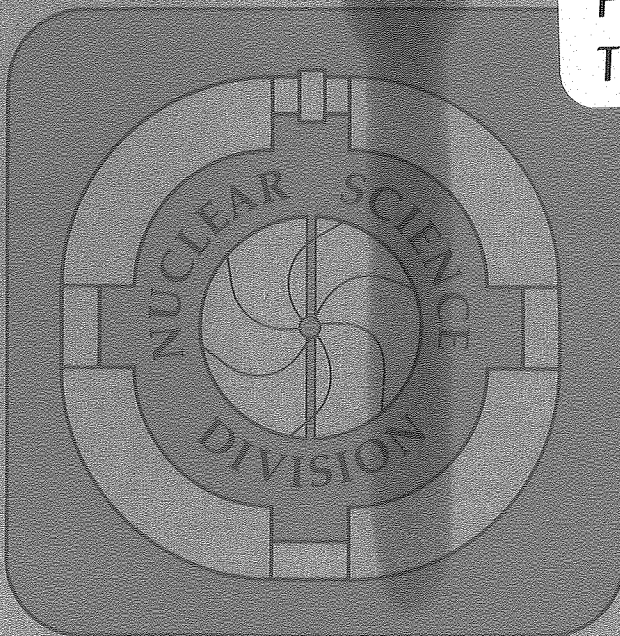
ANGULAR MOMENTUM, STATISTICAL EQUILIBRIUM AND
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March 1981

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ANGULAR MOMENTUM, STATISTICAL EQUILIBRIUM AND SEQUENTIAL FISSION IN
VERY ASYMMETRIC SYSTEMS

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Abstract

The in- and out-of-plane angular distributions for fission fragments in coincidence with projectile-like products from the reaction of 252 MeV ^{20}Ne with ^{197}Au and ^{238}U have been measured. The results are compared to a statistical model which has successfully explained γ -ray anisotropies from a heavy symmetric system. The agreement is rather good after proper consideration of the direction of the line-of-centers at contact.

PACS 25.70 Fg , 25.70 Hi

This work was supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics of the U.S. Department of Energy under Contract No. W-7405-ENG-48.

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The measurement of the internal spin and its alignment for reaction partners from deep-inelastic heavy-ion collisions (DIC) has become an important tool for studying the process of angular momentum transfer. The measurement of fluctuations in the spin components provides a good test of whether statistical equilibrium of the angular momentum bearing modes of the dinuclear complex is achieved in a DIC.¹ Evidence for statistical equilibrium has been observed in symmetric reactions which have been studied by means of γ -ray angular distributions. In the very asymmetric $^{20}\text{Ne} + ^{197}\text{Au}$ and ^{238}U systems the statistical excitation of a number of angular momentum bearing modes is strongly suppressed. In particular, a large difference in the moments of inertia of the two reaction partners will increase the amount of energy necessary to excite any mode in which the small fragment is forced to rotate (wriggling, bending and twisting¹⁻³). Excitation of the only surviving mode (tilting) predicts a minimum in the angular distribution of sequential fission fragments along the line-of-centers.⁴ But the direction of the line connecting the centers of the two nuclei at contact is not generally colinear with the laboratory recoil direction and is dependent on energy loss.

The statistical equilibrium model that we employed has been developed by Moretto and Schmitt¹ and Moretto, Blau and Pacheco.² In this model the fixed aligned components of the fragments angular momenta couple to angular momentum components associated with the internal modes of the complex³ causing the total fragment angular

momentum to become misaligned. When the reaction partners have equal masses, the thermal widths of the angular momentum components are nearly equal in the usual cartesian coordinates (x-axis taken along the line-of-centers). However, as one considers partners with progressively different masses, and hence different moments of inertia, the situation changes dramatically.⁴ The statistical widths of the angular momentum components in the heavy fragment generated by the normal modes are shown individually in Fig. 1 as a function of mass asymmetry.⁴ These widths are projected onto the cartesian coordinates such that $\sigma_x^2 = \sigma_{\text{tilt}}^2 + \sigma_{\text{twist}}^2$ and $\sigma_y^2 = \sigma_z^2 = \sigma_{\text{bend}}^2 + \sigma_{\text{wrig}}^2$. In general terms, if the angular momentum is predominantly perpendicular to the line-of-centers, an in-plane anisotropy arises when $\sigma_x^2 \neq \sigma_y^2$, i.e., at large mass asymmetries ($\sigma_x^2 \approx \sigma_{\text{tilt}}^2 > \sigma_y^2 \approx \sigma_{\text{bend}}^2$). Thus very asymmetric reaction systems should provide an excellent test of the excitation of selected normal modes and of the statistical model in general.

Experimental techniques used to measure the spin and its alignment for DIC products include continuum γ -ray,^{5,6} alpha particle^{7,8} and sequential fission fragment⁹⁻¹² angular distributions. If one considers only reactions with the most negative Q-values, these studies have shown that in-plane anisotropies are small, with the exception of ref. 12. Admittedly, each technique has some drawback, continuum γ -rays are rather insensitive to σ_x and σ_y , whereas alpha-particle distributions must contend with large values of K_0 (the width of the projection of the total spin on the separation axis) relative to σ_x

or σ_y . In-plane sequential fission studies, which should be the most sensitive to differences between σ_x and σ_y , have given conflicting results. In Refs. 9 and 10 an in-plane anisotropy was observed at low Q-values which diminished at high Q-values; however, no such anisotropies were found for a similar system in Ref. 11. For such systems (asymmetry of 0.7) the statistical model predicts only a very small in-plane anisotropy ($\sim 1.1:1$). The $^{20}\text{Ne} + ^{197}\text{Au}$ and ^{238}U systems present a situation where this model predicts a strong in-plane anisotropy (2:1) which should peak perpendicular to the line-of-centers at contact.

A beam of 252 MeV ^{20}Ne from the 88" cyclotron was incident on targets of either $915 \mu\text{g}/\text{cm}^2$ ^{197}Au or $922 \mu\text{g}/\text{cm}^2$ $^{238}\text{UF}_4$. Projectile-like products were detected in a solid state telescope ($11 \mu\text{m} \Delta E$, $300 \mu\text{m} E$, $d\Omega = 3 \text{ msr}$) fixed at -30° . This angle is slightly behind or right at the classical grazing angles (26° and 30° , respectively). Fission fragments were detected in coincidence on the opposite side of the beam in an array of ten single element surface-barrier detectors ($d\Omega = 9 \text{ msr/detector}$), five in-plane and five out-of-plane. This array was moved to cover the angular region between $+30^\circ$ and $+160^\circ$ in-plane as well as between 0° and 75° out-of-plane along and perpendicular to the laboratory recoil axis. Fission fragments were unambiguously identified in a two-dimensional map of fission fragment energy versus time. The data were transformed event by event into the rest frame of the recoiling target nucleus using the energy, charge and angle of the

light product and the energy and angles (θ, ϕ) of the fission fragment. The measured angular distributions are presented in Figs. 2 and 3 for the $^{20}\text{Ne} + ^{238}\text{U}$ system as a function of Q-value. The data have been integrated over the fission fragment energy and the atomic number of projectile residues ($6 \leq Z \leq 14$). The direction $\phi^H = 0$ was arbitrarily chosen to coincide with the laboratory recoil angle as is traditional.⁹⁻¹¹ The sequential fission events observed at small Q-values have a small in-plane anisotropy. The anisotropy disappears at intermediate Q-values; however, for the most inelastic collisions a strong minimum is seen approximately perpendicular to the lab recoil direction. Statistically significant angular distributions from reactions with ^{197}Au (not shown) were obtained only at large Q-values. The position of the minimum and the anisotropies of these angular distributions are essentially the same as those shown for the most inelastic ^{238}U data.

In order to extract quantitative values for the spin polarization of the heavy fragment we have fit the angular distribution data to the generalized function of the statistical model of Broglia et al.^{13,2} In this description the three cartesian widths σ_x , σ_y and σ_z (defined such that x lies along the line-of-centers) appear explicitly along with the projection of the spin on the alignment axis, I_z , and the projection of I on the fission separation axis, K_0 . Finally, one must determine the direction of the line-of-centers of the intermediate complex at the time of separation with respect to the traditional reference direction, the laboratory recoil angle. In the limit of an

elastic collision, without loss of orbital angular momentum, the two directions nearly coincide. But whenever there is a decrease in orbital angular momentum between the entrance and exit channels, the direction of the line-of-centers shifts backward in the laboratory system. In the limit of zero orbital angular momentum in the exit channel, the line-of-centers corresponds to the direction of the recoil in the center-of-mass system. The direction of the line-of-centers should vary for the data presented in Figs. 2 and 3 from nearly equal to the lab recoil direction at $Q = -12.5$ MeV to approximately perpendicular to the lab direction at $Q = -150$ MeV! We have allowed for such a shift in the zero point of the angular distribution by another free parameter in the fitted function. This shift parameter, χ_{HF} , was only constrained to be near 0° for the nearly elastic bin and near 90° for the most inelastic bins. The results of chi-squared minimization fitting (K_0 values following ref. 9) are shown by the solid curves in Figs. 2 and 3 and contained in Table I.

From the results of the fitting we find that the statistical model predictions are in good agreement with all of the out-of-plane angular distributions. For, the more stringent test afforded by the in-plane angular distributions this model over predicts the anisotropy, except for the most negative Q -value where the agreement is good. These trends agree with our expectations that the statistical model

represents the long-time limit which is attained in collisions with the largest energy-losses.

A statistical model prediction that the spins of the primary reaction partners be nearly confined to the plane parallel to the line-of-centers was made on the basis of the energetics of the normal modes for a very asymmetric intermediate complex. Such confinement gives rise to large in-plane anisotropies of sequential fission fragments. After due consideration of the direction of the line-of-centers in the rest frame of the heavy recoil (where the data are presented), the statistical model prediction was shown to compare well in the limit of large Q values.

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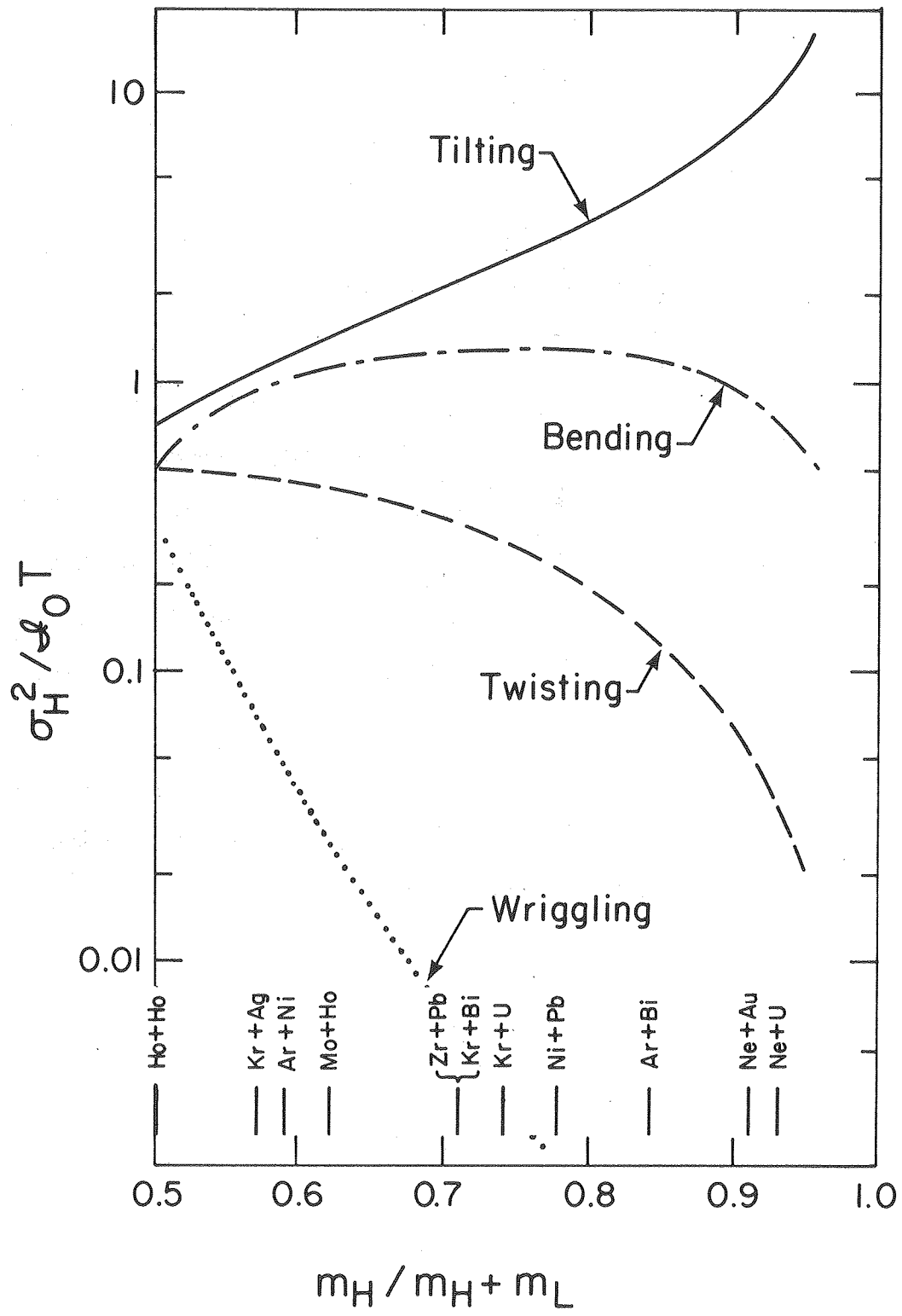
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Table 1. Results of angular distribution fitting including the rotation angle χ_{HF} , errors are given in parenthesis.

Q Value (MeV)	K_0	I_z	σ_x	σ_y	σ_z	χ_{HF}
		(h units)				(degrees)
-12.5	7.3	17.7(0.5)	3.0(0.6)	6.5(0.4)	2.8(0.4)	8.(7.)
-37.5	10.4	27.2(0.2)	7.7(0.2)	8.8(0.2)	1.9(0.5)	16.(9.)
-62.5	12.0	31.1(0.3)	9.5(0.5)	5.8(0.7)	3.1(0.7)	90.(9.)
-87.5	13.1	37.9(0.3)	13.0(0.7)	8.6(0.9)	5.3(0.5)	94.(9.)
-150.	15.0	48.3(0.6)	25.9(0.8)	0.2(5.)	14.2(0.7)	96.(2.)
-150.	Statistical model	22.5	9.2	9.2		80°

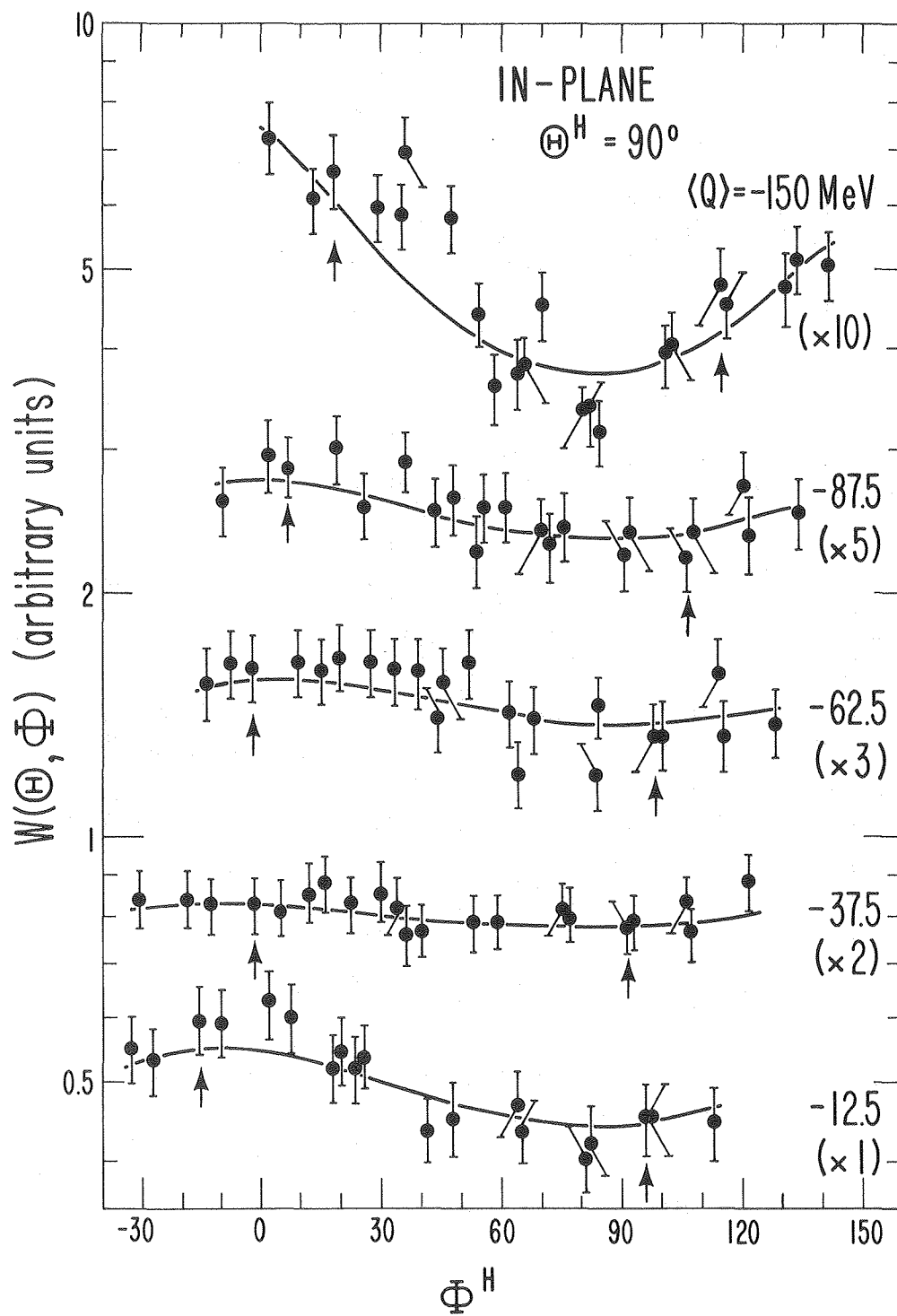
Figure Captions

- Fig. 1. The statistical widths for the normal modes of the dinuclear complex are shown as a function of mass asymmetry of the complex.⁴ The mass asymmetries associated with recent measurements of the angular distributions⁵⁻¹² are also shown.
- Fig. 2. The in-plane angular distributions of sequential fission fragments in the rest frame of the heavy fragment (H) are shown as a function of reaction Q-value for the $^{20}\text{Ne} + ^{238}\text{U}$ system. The arrows indicate the in-plane angles at which out-of-plane measurements were made. The solid curves result from fitting the $W(\theta, \phi)$ function from ref. 13 to the data in each Q-value bin.
- Fig. 3. The out-of-plane angular distributions that correspond to the Q bins of fig. 2 are shown (solid points) along with the fitted functions (solid curves).



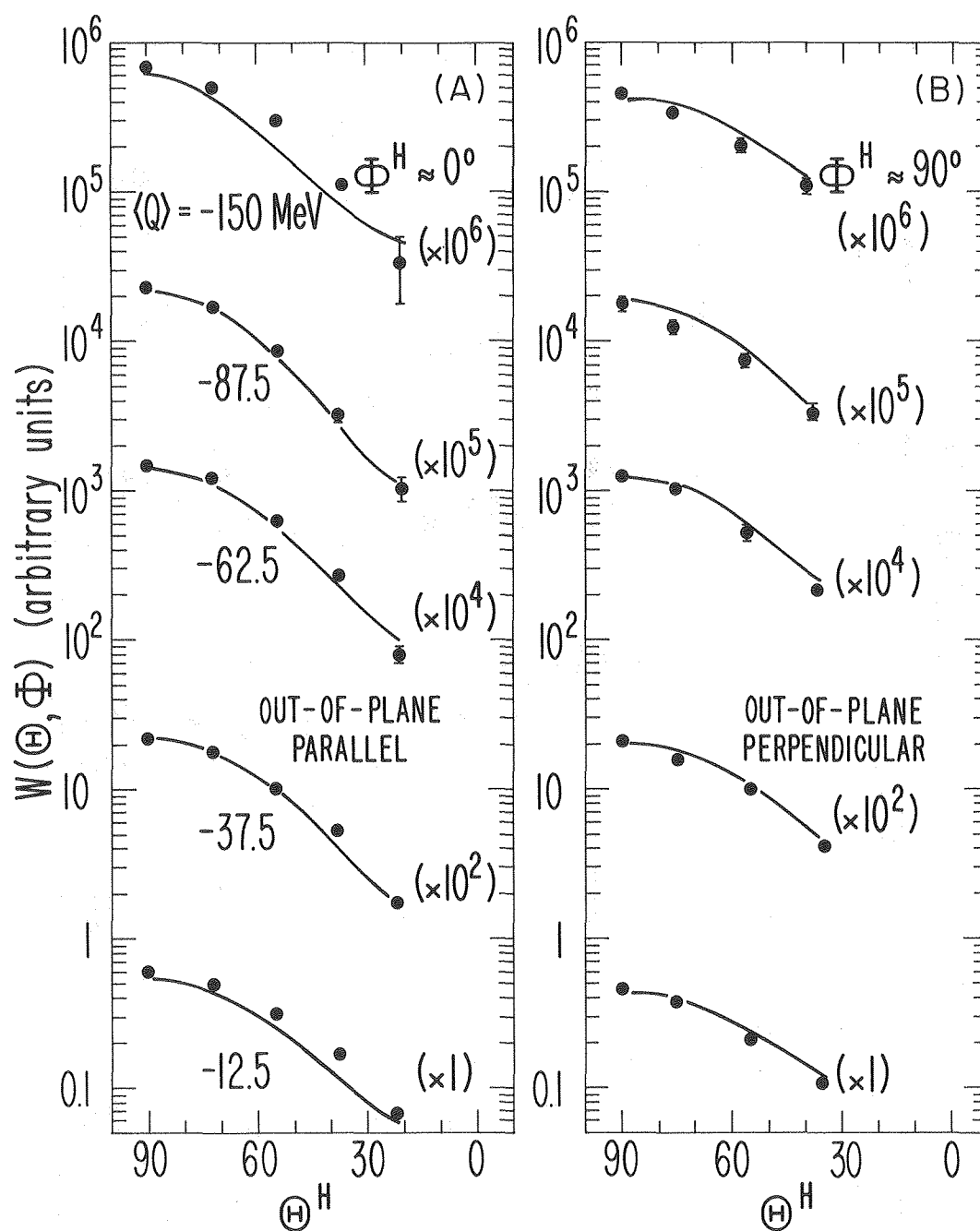
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Fig. 1



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Fig. 2



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Fig. 3